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Dinucleus: A Doorway to Heavy-Ion Fusion

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Heavy-ion fusion reactions of light and medium systems have been analyzed within a two-step compound model involving a dinucleus coupled to particle and breakup channels, as well as to the equilibrated compound nucleus. The fused configuration is reached from the entrance channel only via the dinucleus. The resulting fusion cross sections, defined as the summed particle-emission cross sections from the equilibrated system, are in reasonable agreement with the data.

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In the last several years heavy-ion fusion reactions have attracted considerable interest, both theoretical and experimental.[1] More than half a dozen models have been proposed, ranging from the more sophisticated microscopic, time-dependent Hartree-Fock model to simple geometrical parametrizations. Several facts have emerged from these studies, the more important of which is that the simple one–degree-of-freedom description, usually called the entrance-channel model, is not fully adequate. For a recent review we refer the reader to Ref. 1.

In this Letter, we develop a model for heavy-ion (HI) fusion which incorporates *both* the entrance-channel effects and the compound-nucleus characteristics in a consistent way. We feel that a model realistic enough to deal with HI fusion must contain, at least, these effects.

We emphasize at this point that by "entrance-channel effects" we do not mean just the restriction imposed through transmission factors calculated with a given entrance-channel potential; rather, we also incorporate the effects arising from the formation of an intermediate dinucleus configuration that precedes the final equilibrated compound nucleus. We allow the HI system to emit particles both from the intermediate stage as well as from the compound nucleus. The dinucleus system is also allowed to break up into two fragments. The need for such a multistep description of heavy-ion fusion has already been pointed out in previous publications.[2,3]

Figure 1 shows the sequence of events that eventually lead to fusion. The coupling between the dinucleus and the compound nucleus is treated statistically within the multistep compound model of Agassi,

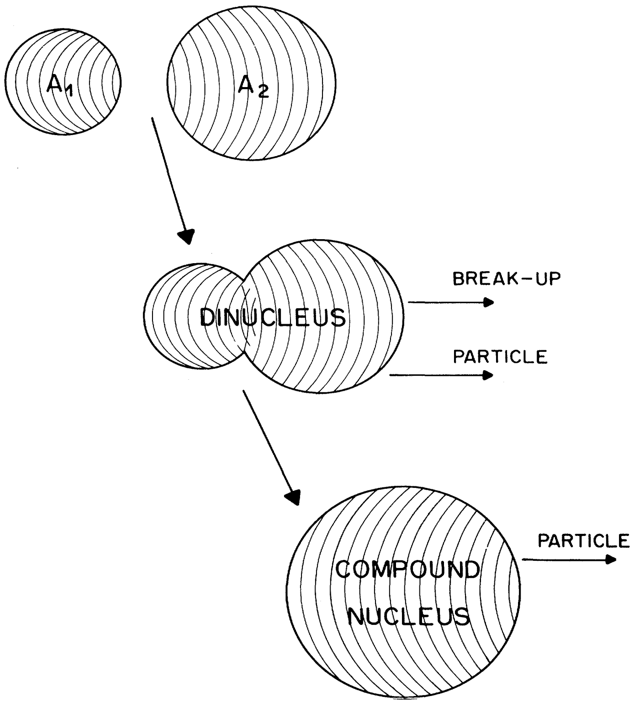

FIG. 1. A schematic representation of the two-step compound fusion process.

Weidenmüller, and Mantzouranis.[4] The partial cross section for a transition, leading to particle emission from the compound nucleus, is calculated as

$$\sigma_{fi}(J) = (\pi/k_i^2)(2J+1)\,T_f^c \Pi_{cd} T_i^d, \tag{1}$$

where T_i^d is the transmission coefficient describing the formation of the dinucleus from the entrance channel, T_f^c is the corresponding particle-emission transmission coefficient from the compound nucleus, and Π_{cd} is an internal mixing matrix element describing the coupling between the dinucleus and the compound nucleus. The full internal mixing matrix is given by the inverse of

$$\Pi^{-1} = \begin{pmatrix} 2\pi\rho_d\Gamma_d^{\uparrow} + T^{\downarrow} & -T^{\downarrow} \\ -T^{\downarrow} & 2\pi\rho_c\Gamma_c^{\uparrow} + T^{\downarrow} \end{pmatrix}, \tag{2}$$

where the internal mixing factor $T^{\downarrow}$ is

$$T^{\downarrow} = (2\pi)^2(\rho_c\rho_d)^{1/2}\langle V_0^2\rangle, \tag{3}$$

ρ_d and ρ_c are, respectively, the J-dependent densities of states of the dinucleus and compound nucleus, $\Gamma^{\uparrow}$ is the escape width, given by

$$\Gamma_d^{\uparrow} = \Gamma_d^{\text{breakup}} + \Gamma_d^{\text{particle}}, \tag{4}$$

$$\Gamma_c^{\uparrow} = \Gamma_c^{\text{particle}}, \tag{5}$$

and $\langle V_0^2\rangle$ is an overall coupling constant, which is taken as a free parameter.

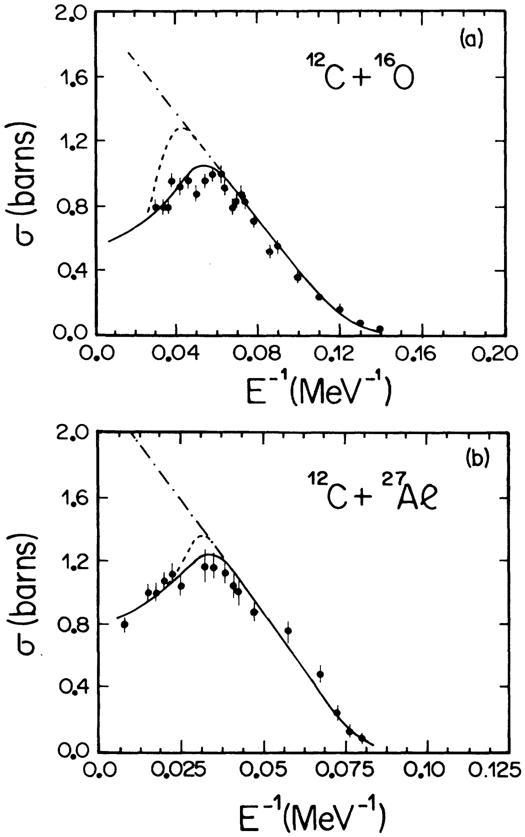

FIG. 2. σ_F for the systems (a) $^{12}C + ^{16}O$ and (b) $^{12}C + ^{27}Al$. The solid curve corresponds to our calculated σ_F. The dashed curve represents $\sigma_F + \sigma_{\text{pre}}$. The dash-dotted curve is the total-reaction cross section, calculated from the entrance-channel transmission coefficient. The data points were collected from Ref. 1.

The density of states of the dinucleus is calculated on the assumption of a sticking situation, in the Fermi-gas model. ρ_c is the usual compound-nucleus density of states. The fusion cross section is calculated from Eq. (1) by summation over all particle-emission channels from the compound nucleus and over J. The transmission coefficients were calculated, by use of the Hill-Wheeler form, with a global real potential of the Woods-Saxon type, whose parameters were adjusted, together with $\langle V_0^2\rangle$, to give the best account of the data for a large variety of light-heavy and medium-heavy systems. The adjusted nucleus-nucleus potential is

$$V(R) = -20.11[R_1R_2/(R_1+R_2)]\{1+1.014[(N-Z)/A]^2\} \times \{1+\exp[(R-R_0)/0.4454]\}^{-1}\ \text{MeV},$$
$$R_{1,2} = 1.2998A_{1,2}^{1/3} - 0.4286A_{1,2}^{-1/3}\ \text{fm},\quad R_0 = R_1+R_2+0.29\ \text{fm}. \tag{6}$$

To simplify the calculation, we have explicitly considered only the collective (rotational) degrees of freedom in constructing the level density of states of the dinucleus. To take partially into account the intrinsic degrees of freedom, we merely adjust the level-density parameter a {which appears in the Fermi-gas formula as $\exp[2(aE^*)^{1/2}]$} to be $A/8x$, with x being a parameter. Usually $x=1$. Here we find, motivated by the result of Ref. 2 that the internal energy of the composite nucleus is $\Delta Q = 0.27A_{\text{CN}}$, that a_d (of the dinucleus) is related to a_c (of the compound nucleus) by

$$a_d \cong 0.2a_c, \tag{7}$$

which implies that $x=5$.

We show in Fig. 2 a sample of our results obtained with $\langle V_0^2\rangle = 21.5$ MeV. The drop in σ_F, seen in what is called region II, is attributed, within our model, to the increased importance of the dinucleus breakup channel. We have repeated the calculation for more than twenty systems, obtaining an overall reasonable agreement with the data. The details of these calculations will be published elsewhere.[5] We may mention that the energy corresponding to maximum fusion cross section is systematically well predicted. Further, the feature of σ_F vs $E_{\text{c.m.}}^{-1}$ that depends on the entrance channel, and which is reflected by positive, null, or negative values of V_{cr},[1] is nicely predicted by our

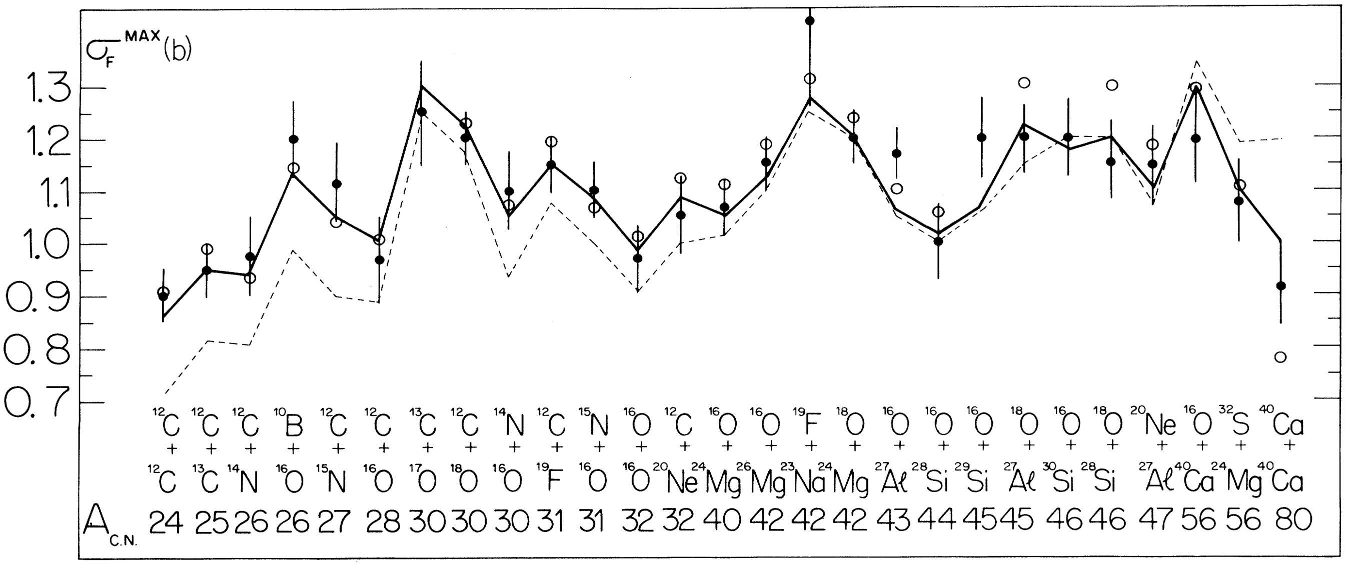

FIG. 3. Maximum fusion cross section $\sigma_F^{\max}$ measured for various systems (filled circles). Data were taken from original papers cited in Refs. 1 and 5. The open circles are our calculated $\sigma_F^{\max}$. The solid curve is the empirically found $\sigma_F^{\max}$ from the modified statistical yrast-line model (Ref. 2). The dashed curve is the statistical yrast-line model prediction of Ref. 6.

model (e.g., $^{12}C+^{16}O$, $^{16}O+^{27}Al$, and other light-heavy systems have $V_{cr} < 0$ while $^{16}O+^{40}Ca$ or $^{40}Ca+^{40}Ca$ exhibit $V_{cr} \geqslant 0$).

The contribution of particle emission from the dinucleus (doorway) configuration is shown in Fig. 2, summed to σ_F (dashed line). We see clearly that this effect is mostly important in the region of maximum σ_F. This implies that preequilibrium particle emission should be reasonably copious at these energies. Further, there seems to be a clear connection between the value of $\sigma_F^{\max}$ and the cross sections for dinucleus particle emission (preequilibrium) σ_{pre}; the larger $\sigma_F^{\max}$, the smaller σ_{pre}.

For completeness, we show in Fig. 3 the calculated values of $\sigma_F^{\max}$ for 24 systems. Our results come out quite reasonable, and follow closely the trend of the data and the empirically determined $\sigma_F^{\max}$ of Ref. 2. For comparison, we show in the same figure the prediction of the statistical yrast-line model of Lee, Matsuse, and Arima.[6]

Before we close it is tempting to suggest that the dinucleus, as it is treated in our model, is a geometrical visualization of overlapping quasimolecular resonances. As is well known, HI systems such as $^{12}C+^{12}C$, and $^{16}O+^{12}C$ exhibit, in the elastic and compound-nucleus (fusion) excitation functions, intermediate structure, which is commonly related to the formation of isolated quasimolecular resonances. It is also common knowledge that heavier, or structurally more complex, systems do not show this behavior. One is therefore led to the suggestion that these resonances, which may be isolated in, e.g., $^{12}C+^{12}C$ at the energies considered, $E_{\text{c.m.}}/A \sim 2$–3 MeV, become overlapping at higher energies and/or in other systems. The picture which emerges is that of a nuclear reaction mediated by several classes of overlapping compound resonances which couple among themselves and with the open channels. Theories of such reactions have been developed by Agassi, Weidenmüller, and Mantzouranis,[4] Feshbach, Kerman, and Koonin,[7] and Friedman *et al.*[8]

We have chosen the Agassi-Weidenmüller-Mantzouranis[4] approach as it is the more general, though technically more involved approach. The development of Feshbach, Kerman, and Koonin,[7] which describes the same physics, is simpler and would probably be more adequate, if more than two classes of resonances are required. Finally, Ref. 8 discusses other statistical features of multistep compound reactions, such as Ericson fluctuations and time evolution. These topics, as well as a more detailed account of our results, will be discussed fully in a longer article under preparation.[5]

In conclusion, the fact that the general trends of the fusion excitation functions are reasonably well predicted by our model, which uses the global entrance channel potential plus an average dinucleus–compound-nucleus mixing parameter, for more than twenty HI systems, clearly indicates that the most important features of the dynamics are adequately taken into account in the present calculation. The crucial new ingredient is the presence of the dinucleus, which acts as a "doorway" to fusion. The explicit consideration of the competition between fusion, on the one hand, and doorway breakup and particle-emission channels, on the other hand, is an important feature of our model, which helps account naturally and consistently for the downward drop of σ_F in region II seen in light heavy-ion systems, and thus avoids the introduction of a "region III,"[9] in complete agreement with Ohta *et al.*[10] Some indirect experimental evidence for the existence of the dinucleus has already been reported.[11]

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